INTER-NOISE 2006
3-6 DECEMBER 2006
HONOLULU, HAWAII, USA

An assessment of NASA Glenn's aeroacoustic experimental and predictive capabilities for installed cooling fans Part 2: Source identification and validation

L. Danielle Koch[a]
NASA Glenn Research Center
21000 Brookpark Road
Mail Stop 54-3
Cleveland, OH 44135
USA

Dale E. Van Zante[b]
NASA Glenn Research Center
21000 Brookpark Road
Mail Stop 54-3
Cleveland, OH 44135
USA

Mark P. Wernet[c]
NASA Glenn Research Center
21000 Brookpark Road
Mail Stop 77-1
Cleveland, OH 44135
USA

Gary G. Podboy[d]
NASA Glenn Research Center
21000 Brookpark Road
Mail Stop 54-3
Cleveland, OH 44135
USA

ABSTRACT

Quiet, high performance electronics cooling fans are needed for both commercial applications and future manned space exploration missions. Researchers at NASA Glenn focusing on aircraft engine noise, have long been familiar with the challenge of reducing fan noise without sacrificing aerodynamic performance. Is it possible to capitalize on the lessons-learned in aircraft engine noise reduction to identify inexpensive ways to improve the aerodynamic and acoustic performance of electronics cooling fans? Recent tests at NASA Glenn have begun to look for answers to this question.

The overall aerodynamic and acoustic performance of a commercially available, spaceflight qualified 80 mm diameter axial flow fan has been measured using an automated plenum in accordance with ISO 10302 in the hemi-anechoic chamber of NASA Glenn's Acoustical Testing Laboratory. These measurements are complemented by detailed aerodynamic measurements of the inlet, exhaust, and rotor wake regions of the fan using Particle Image Velocimetry and hot-wire probes. A study of preliminary results yielded recommendations for system designers, fan manufacturers, and researchers.

1 INTRODUCTION

Quiet fan-cooled products are the result of painstaking attention to detail—by both the fan manufacturer and the product designer. The complexity of the aerodynamics and acoustics of small cooling fans can easily be underestimated given the great number of fans in use. If noise is simply a nuisance, and power consumption and product size and weight unimportant, it can be easy to overlook an underperforming fan. However, as in the case of fans destined for crewed spaceflight, if noise verges on a safety hazard and power consumption, weight, and size are to be minimized, steps can and should be taken early in the design cycle to optimize fan installations.

[a] Email address: L.Danielle.Koch@nasa.gov
[b] Email address: Dale.E.VanZante@nasa.gov
[c] Email address: Mark.P.Wernet@nasa.gov
[d] Email address: Gary.P.Podboy@nasa.gov

Continuing challenges experienced with noise onboard the International Space Station (ISS) have prompted Goodman [1] to call for a more concerted effort to address the acoustic design of spaceflight hardware. Goodman [1] lists several lessons learned which are valuable for future long duration crewed missions: a) program noise requirements should be well founded and treated as true requirements rather than goals; b) noise limits should be stipulated for components as well as full systems; c) acoustics should be included early in the design process; d) complicated systems such as modules and payload racks should have a documented noise control plan identifying all noise sources, proposed development and verification tests; e) all modules should undergo a common, well-controlled set of verification tests; f) an appropriate level of oversight needs to be applied during system design; and finally, g) system designers would benefit significantly with access to a well experienced independent team able to provide design support during system development.

Most of these recommendations stem from a common challenge: noise problems are often discovered late in product development when few feasible remedies remain to be applied. Grosveld, Goodman, and Pilkinton [2] present a number of case studies in noise control efforts for the International Space Station. In one case, fans had been determined to be the dominant source of noise that caused a number of experimental payloads installed in the EXPRESS (Expedite the Processing of Experiments to Space Station) rack system to exceed acoustic emission limits. To bring the systems into compliance, mufflers were designed and installed. While the mufflers successfully reduced system noise, the solution invites the curious mind to wonder what other changes could have been made to make the fan run intrinsically quieter.

Noise source reduction is substantially different than noise control. Work to reduce the fundamental mechanisms of noise generation may lessen the need for noise control devices such as mufflers and enclosures, as well as the need for personal hearing protection. Considerable efforts have been made to improve the fundamental understanding of the various sources of fan noise. Fitzgerald and Lauchle [3] describe research to characterize the noise generated by a computer cooling fan fitted with a short annular duct. As Fitzgerald and Lauchle [3] explain, once the mechanisms of noise generation are understood, effective noise control methods can be more clearly identified. Interpretation of a fan noise spectrum is not simple, but significant progress has been made associating features of the fan and its operating conditions to the resulting noise signature. Fitzgerald and Lauchle [3] provide a table of noise sources for subsonic fans, which are summarized here.

Tones at constant phase blade passing harmonics can be created by steady spatial distortions in the flow ingested by the fan, spatial variations of boundary layer thickness, *and* the interaction of the rotor blades with the potential fields of nearby stationary objects (i.e. motor struts, guide vanes). To reduce these tones, all three sources need to be addressed. Effective noise source reduction solutions will depend on identifying which of the contributing noise generation mechanisms dominate for any given installation. This implies a shared challenge for fan and system designers. As an example, efforts by a system designer to better condition the flow entering a fan may marginally reduce system tone noise if the dominant source is the interaction of the wakes of the rotor blades with the fan motor struts. Likewise, efforts to change fan rotor or strut geometry to reduce rotor/stator interaction noise may not yield the desired system noise reduction if the fan is installed where nearby hardware causes severe non-uniformities in the flow at the fan inlet.

Tones at varying phase blade passing frequency can be attributed to boundary layer thickness changes that vary in time and space, inlet turbulence, and slowly varying inlet distortions. Tones at shaft rotational frequency harmonics can be caused by the combination of a number of blade-to-blade irregularities including: variations in tip clearance, stagger angle, and skew; irregularly positioned blades; blade form imperfections; as well as long-time scale blade boundary layer variations. Peaks in the fan noise spectrum at non-rotational ordered frequencies can occur if there are rotating inlet distortions and mechanical vibrations of the rotor blades. And finally, Fitzgerald and Lauchle [3] list three sources of loading associated with varying frequency and broadband noise: detailed variations in the annulus boundary layer, short-term, small scale inlet turbulence, and short-term boundary layer fluctuations. Again, efforts to reduce the noise of any given fan installation will depend on correctly identifying and addressing the most dominant source mechanisms.

Sandwiched between the task of understanding the fundamentals of fan noise generation and the task of prescribing effective solutions to reduce noise sources is the challenge of developing software for computing noise. Software that can compute aerodynamically generated noise is developed by numerically implementing theories and validating embedded models and results against measured quantities. Validated noise prediction software, be it suited for conceptual design or detailed analysis, can help fan manufacturers to identify design changes to improve the acoustic performance of their products.

The main focus for researchers in the Acoustics Branch at the NASA Glenn Research Center has been investigating the fundamentals of noise generation, developing noise reduction methods, and developing validated noise prediction tools for aircraft engines. Anticipating a possible need to provide increased support for those designing fan-cooled spaceflight hardware, the facilities, instrumentation, and expertise at the NASA Glenn Research Center were exercised to study the performance of an electronics cooling fan in an effort to assess existing strengths and the direction of future work.

2 DISCUSSION OF EXPERIMENTAL INVESTIGATIONS

A suite of acoustic and aerodynamic experiments that used a representative spaceflight qualified, axial cooling fan was prescribed for three primary reasons: a) to determine if the facilities and instrumentation historically used for acoustic verification tests of spaceflight hardware could be used for fan noise source identification and prediction code validation research; b) to determine if the facilities and instrumentation typically used to diagnose aerodynamic performance issues for a much larger class of fans could measure desired quantities in suitable detail for the smaller fan, and c) to characterize the aerodynamic and acoustic performance of the fan itself. While the experiments are valuable in and of themselves, the data can be useful for the development of noise prediction codes.

An 80 mm spaceflight qualified fan is shown in Figure 1 and nominal specifications given adjacently in Table 1. The fan had 5 rotor blades, and 4 equally spaced radial motor struts downstream of the rotor. The rotor hub contour was cylindrical. The rotor shroud contour was more complicated: cylindrical over roughly the middle two-thirds of the axial chord, rounded outwards at the blade leading and trailing edge regions, with four regions where the circular geometry blended with the square mounting flanges. Based solely on visual inspection of the fan, suspected leading mechanisms of noise generation could include inlet distortion, rotor-stator interaction, tip clearance flows, and blade form imperfections.

The widespread lack of sufficiently detailed catalog data for small, low-subsonic axial cooling fans has led to the development of automated systems such as that reported by Schmitt [4] which can be used to quickly map the overall aerodynamic and acoustic performance of a fan from free delivery to completely blocked conditions. Verification data from this type of test is essential for the system designer, and is a useful beginning for advanced diagnostics and noise prediction code development work.

The fan was tested using the automated plenum described by Schmitt [4] using a 19 microphone array in NASA Glenn’s Acoustical Testing Laboratory (Figure 2) in accordance with ISO 10302 [5] and ISO 3744 [6]. Measured pressure rise is plotted against flow rate, as shown in Figure 3, for the fan operating at a constant rotational speed of 3300 rpm with and without a simple inlet duct approximately 80 mm (1 fan diameter) in length. No attempt was made to adapt the inlet duct to the contoured inlet of the fan. The A-weighted overall sound power level for each of the throttled conditions is plotted as a function of flow rate in Figure 4. Examination of these curves is useful for a system designer, identifying the point of maximum pressure rise and minimum noise (occurring at operation near 40 m^3/hr). Comparisons of the ducted and unducted fan indicate addition of the duct can increase pressure rise at this point while simultaneously decreasing overall noise emissions. Additional discussion of these results is provided by Van Zante et al. [7].

While well suited for fan noise verification testing, changes to the facility data acquisition system would be required to better identify the fundamental mechanisms of noise generation for cooling fans and for code validation work. Figure 5 shows the third-octave spectra of the A-weighted sound power levels for the fan at free delivery and Figure 6 shows power spectral density of sound pressure level as a function of frequency at Microphone 2 (see Figure 2) for the ducted and unducted fan at free delivery. While peaks are evident (BPF~275 Hz) on both the third-octave and narrowband spectra, the relative contribution of broadband and tone noise to the overall noise emissions cannot be well separated. By recording sound pressure levels synchronized with the fan rotation, ensemble-averaging the data in the time-domain as described by Envia [8] can be used to help to illuminate dominant sources. Efforts to decipher the noise signature of the fan are greatly needed to guide the direction of the noise prediction development. Noise generation mechanisms are typically modeled individually (i.e. the effort to model broadband sources is separate from the effort to model tone sources), given the reality that producing accurate noise estimates can quickly become computationally intensive.

Guided by the possibility that inlet distortion, rotor-stator interaction, and tip clearance flows could contribute significantly to the noise emissions from the fan, two types of aerodynamic tests were conducted for the isolated fan. First, two- and three-dimensional Particle Image Velocimetry (PIV) measurements were taken to characterize the flow upstream and downstream of the fan. Second, a hot-wire probe was used to characterized the rotor blade wakes by measuring two components of the velocity in a plane parallel to the fan exit located between the rotor blade trailing edge and the fan motor struts. Both types of aerodynamic tests have been routinely used in ongoing aircraft engine noise reduction research, some of which is described in References 9 and 10.

Orientation of the PIV measurement planes at the fan inlet is shown in Figure 7, and a more detailed description of the experimental setup is given by Van Zante, et al. [7]. Valuable for both qualitative and quantitative purposes, the PIV measurements confirm the presence of significant distortion at the inlet to the rotor. Fan dimensions in the plots have been normalized by the fan duct diameter.

Figure 8 shows streamlines superimposed on a contour plot of the axial velocity in the plane perpendicular to the fan inlet at the fan centerline. Without an inlet duct to condition the flow ingested by the fan, both the axial and radial components of velocity contribute significantly to the total absolute velocity at the fan inlet. Figures 9 and 10 show the distributions of the axial and radial components for two measured phase steps extracted at the fan inlet plane, which indicate radial velocities on the order of the axial component. The presence of significant radial velocity at the blade leading edge differentiates the cooling fan from aircraft engine fan stages, the latter include inlets designed to provide flow at the fan face that is primarily axial and as circumferentially uniform as possible. The three-dimensional PIV data reveals the impact of the complicated shroud and mounting flange geometry. Data reveal that the flow at the inlet plane is not circumferentially uniform, as shown most clearly in Figure 11 (12.7 mm upstream of the fan face) and less so further upstream in Figure 12 (25.4 mm upstream of fan face).

Tone noise generated by the interaction of the rotor blades with the nearby motor struts depends on the characteristics of the blade wakes. The second aerodynamic test conducted was measurement of the rotor blade wakes using a hot-wire probe. Absolute frame axial and tangential velocity components were measured downstream of the fan blade trailing edge and upstream of the motor struts. Figure 13 shows the distribution of total relative velocity and characterizes the wake of the fan blade, as well as the effect of the large tip clearance. Velocity deficit is computed, and normalized by the velocity deficit at the wake centerline. The normalized velocity deficit is plotted as a function of tangential distance normalized by blade pitch, as shown in Figure 14. Comparison of the measured wake profiles to a wake profile model embedded in an existing rotor-stator interaction code (Envia and Nallasamy [11]) which has been used for optimizing aircraft engine fan geometry to reduce noise, shows relatively good agreement at midspan but significant differences at radial stations nearer to the hub and tip regions.

While both the PIV and hot-wire tests yielded desired flow field data for an unducted fan at free delivery, additional test hardware is needed to enable measurements to be taken at throttled conditions. Hardware should be included to measure velocities for ducted fans, as well.

3 CONCLUSION AND RECOMMENDATIONS

Fan noise reduction poses challenges to fan manufacturers, system designers, and researchers alike. Interpretation of preliminary results yield recommendations for each. For those trying to manufacture low noise fans, inlet flow conditioning should be an area of attention. Attempting to provide circumferentially uniform axial flow at the inlet can improve the aerodynamic and acoustic performance of a fan. Acoustic emission curves for the entire operating range of the fans should be provided to system designers.

For system designers it is recommended to avoid square-to-round adaptations near the fan inlet since the geometry needed to do this distorts the flow entering the fan which can reduce aerodynamic performance and increase noise. Single operating point acoustic data is insufficient for design purposes, and maps of the noise emissions for the entire operating range of the fan are needed.

For researchers, recognize that verification data useful for system designers also provides a useful start for advanced source diagnostics and noise prediction code development work. The existing facilities and instrumentation at the NASA Glenn Research Center can be used for validation work with some adaptation. For acoustic tests, synchronous data must be acquired, and aero tests must be fixtured to allow for the measurement of ducted fan configurations at throttled conditions. Computationally, experience with existing broadband and tone noise codes such as those described by Nallasamy and Envia [12] and Envia [13], well-suited for ducted aircraft engine fan stages, provide a useful start for investigating future noise prediction work for small cooling fans. Since duct theory predicts that tones for this fan would be cut-off, a study of open rotor formulations, such as that described by Huang [14], is required. The direction of future computational work needs to be guided by more detailed experimental investigations attempting to better discern the relative contributions of broadband and tone noise to the overall fan noise emissions.

Recognizing that a) fan noise reduction is important to spaceflight hardware developers as well as to those seeking to fan-cool consumer electronics, b) that there is a demand for support early in product design cycles, and c) fan noise prediction is a challenging problem for researchers, the potential to collaboratively study this area exists. Those interested in continued collaborative research or design support are invited to study the proposal described by Koch and Van Zante [15].

4 ACKNOWLEDGEMENTS

The authors wish to thank Ed Envia for his guidance, Beth Cooper and Paul Passe for support of the Acoustical Testing Laboratory, David Nelson for assistance in data acquisition and helpful advice, Trevor John and Gary Clayo for assistance with PIV measurements. This work was supported by the NASA Fundamental Aeronautics Program.

5 REFERENCES

[1] Jerry R. Goodman, "International Space Station Acoustics," *Proceedings of NOISE-CON 2003*, Inc03_125, (2003).

[2] Ferdinand W. Grosveld, Jerry R. Goodman, and Gregory D. Pilkinton, "International Space Station Acoustic Noise Control—Case Studies," *Proceedings NOISE-CON 2003*, Inc03_117, (2003).

[3] James M. Fitzgerald and G. C. Lauchle, "Reduction of discrete frequency noise in small, subsonic axial-flow fans," Journal of the Acoustical Society of America, **76**(1), 158-166, (1984).

[4] Jeff G. Schmitt, David A. Nelson, and John Phillips, "An Acoustical System for the Acoustical and Aerodynamic Characterization of Small Air Moving Devices," *Proceedings of NOISE-CON 2005*, N05_127, (2005).

[5] *Acoustics-Method for the measurement of airborne noise emitted by small air-moving devices*, International Standard ISO 10302 (1996-12-15): 1996 (International Organization for Standardization, Geneva, Switzerland, 1996).

[6] *Acoustics-Determination of Sound Power Levels of Noise Sources Using Sound Pressure—Engineering Method in an Essentially Free Field over a Reflecting Plane Second Edition*, International Standard ISO 3744 (1994-05-01): 1995 (International Organization for Standardization, Geneva, Switzerland, 1994).

[7] Dale E. Van Zante, L. Danielle Koch, Mark P. Wernet, Gary G. Podboy, "**A**n assessment of NASA Glenn's aeroacoustic experimental and predictive capabilities for installed cooling fans, Part 1: Aerodynamic performance," NASA TM-214448, (2006).

[8] Edmane Envia, "Fan Noise Source Diagnostics Test-Vane Unsteady Pressure Results," NASA TM-2002-211808, (2002).

[9] Gary G. Podboy, Martin J. Krupar, Stephen M. Helland, and Christopher E. Hughes, "Steady and Unsteady Flow Field Measurements within a NASA 22-Inch Fan Model, NASA TM-2003-21329, (2003).

[10] Mark P. Wernet, Michelle M. Bright, and Gary Skoch, "An Investigation of Surge in a High-Speed Centrifugal Compressor Using Digital PIV," NASA TM-2002-211832, (2002).

[11] Edmane Envia and M. Nallasamy, "Design Selection and Analysis of a Swept and Leaned Stator Concept," NASA TM-1998-208662.
[12] M. Nallasamy and Edmane Envia, "Computation of Rotor Wake Turbulence Noise," Journal of Sound and Vibration, **282**(3-5), 649-678, (2005).
[13] Edmane Envia, D. L. Huff, and C. R. Morrison, "Analytical Assessment of Stator Sweep and Lean in Reducing Rotor-Stator Tone Noise," AIAA 96-1791.
[14] Lixi Huang, "Characterizing computer cooling fan noise," Journal of the Acoustical Society of America, 114(6), 3189-3200, (2003).
[15] L. Danielle Koch and Dale E. Van Zante, "Cool and Quiet: Partnering to enhance the aerodynamic and acoustic performance of installed electronics cooling fans," NASA TM-214449, 2006.

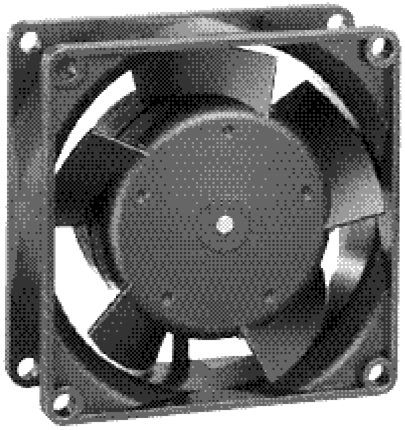

Table 1: Test Fan Description.

Case Dimensions	80 x 80 x 32 mm
Duct Diameter	77 mm
Hub Diameter	42 mm
Number of blades	5
Number of motor struts	4
VDC	24
Maximum Flowrate	54 m^3/hr
Power	2.5 W

Figure 1: Test fan description

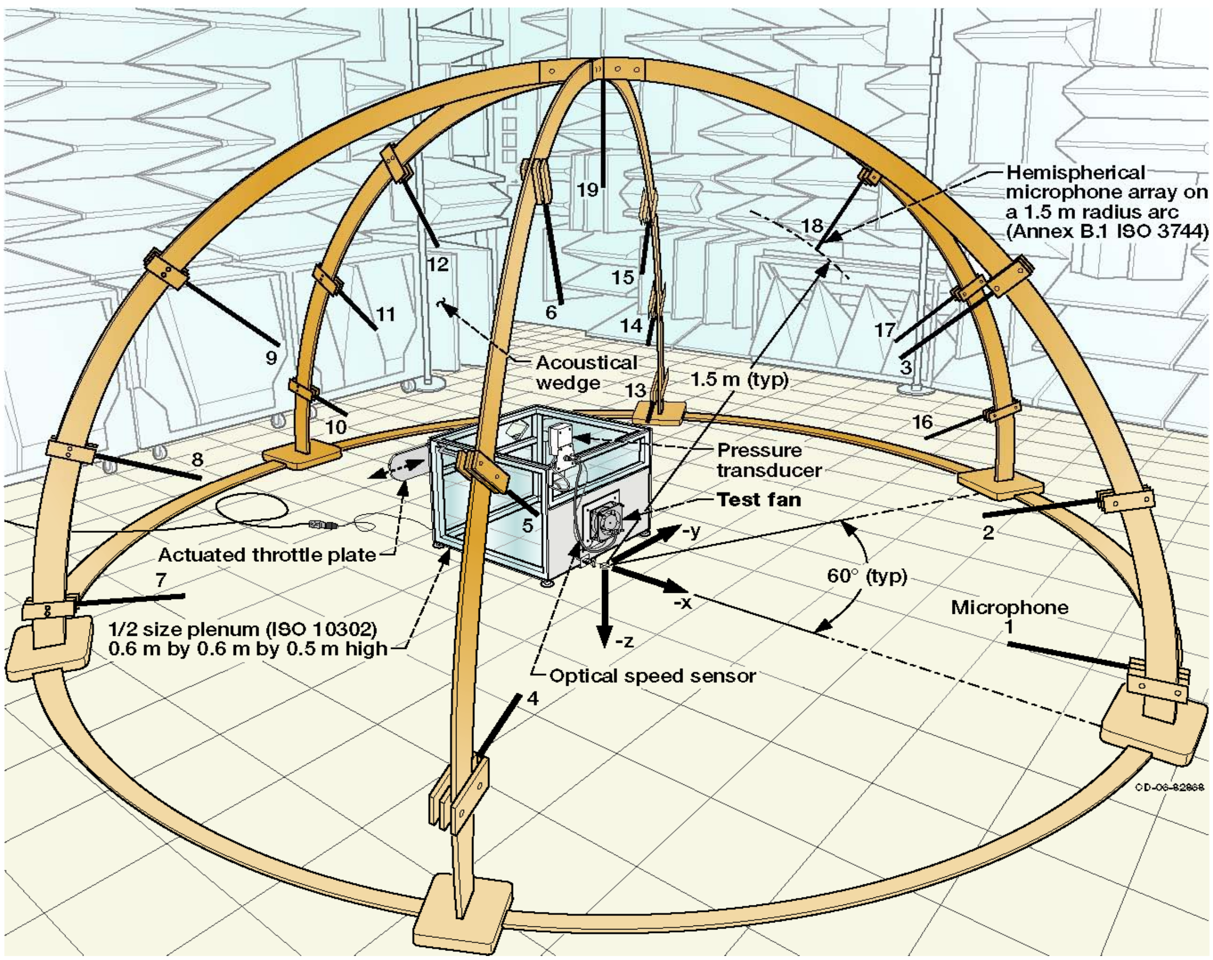

Figure 2: Automated fan plenum and microphone array in the NASA Glenn Acoustical Testing Laboratory

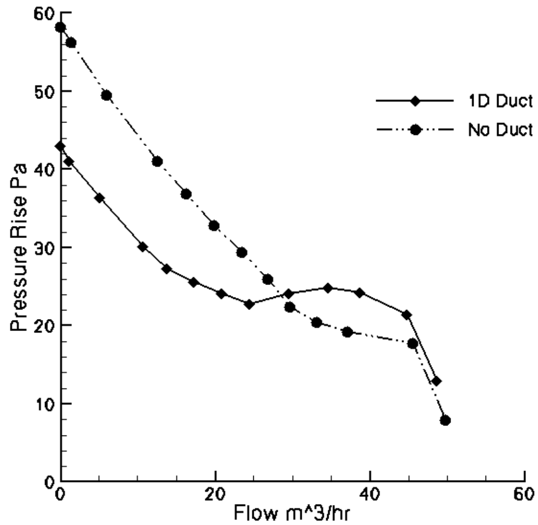

Figure 3: Fan aerodynamic performance map

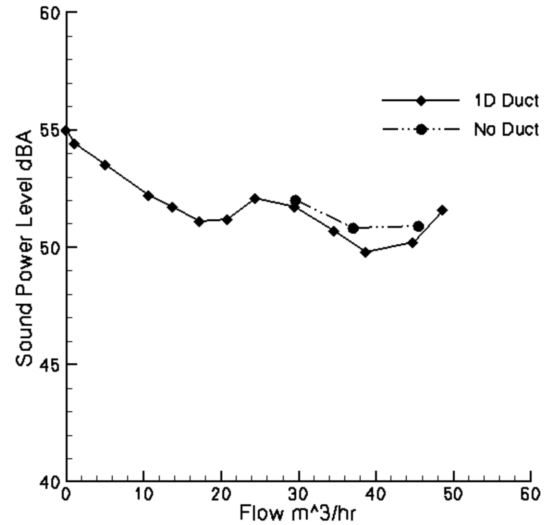

Figure 4: Fan overall sound power map

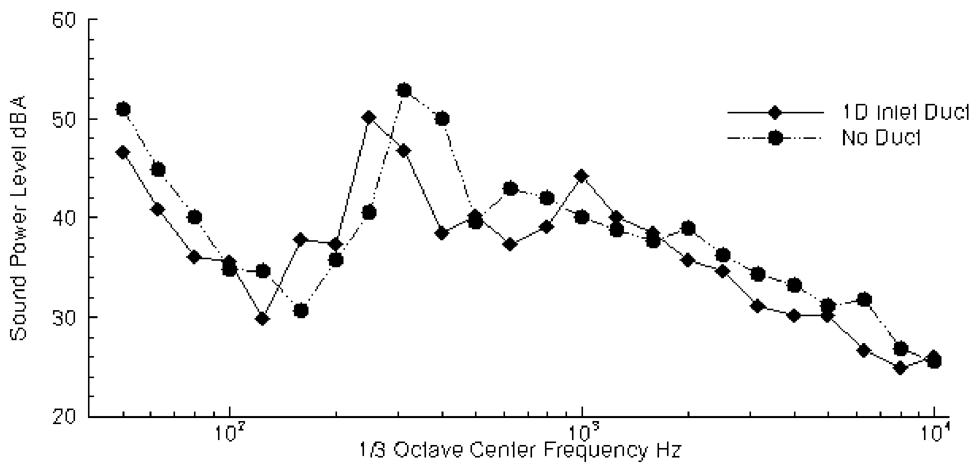

Figure 5: Third-octave fan specta at free delivery

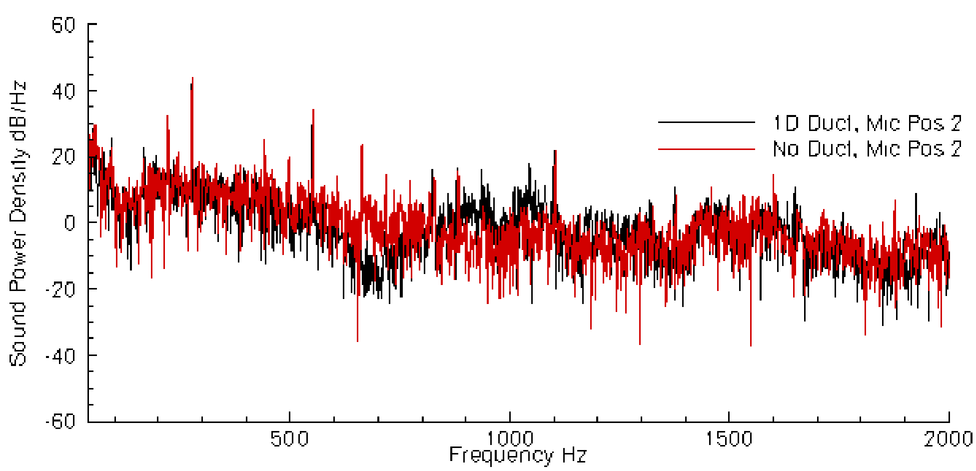

Figure 6: Narrowband fan spectra at free delivery

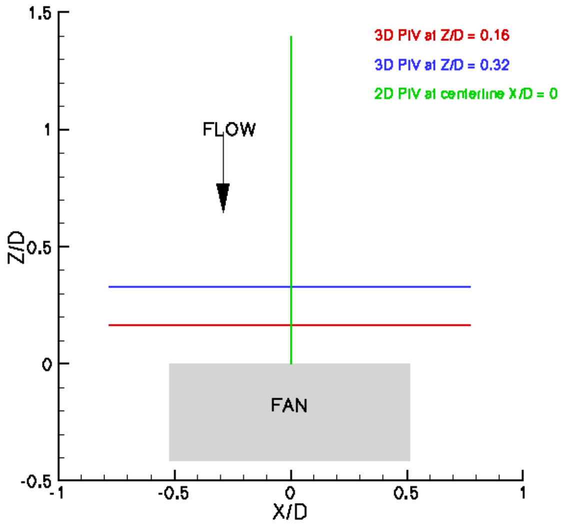

Figure 7: PIV measurement plane locations

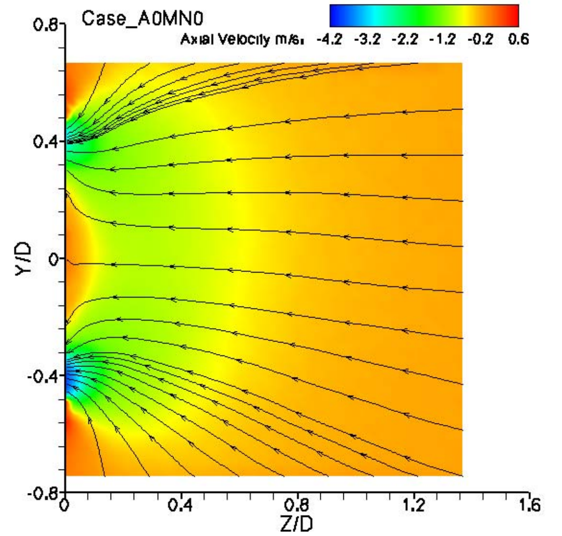

Figure 8: Axial velocity distribution at fan centerline

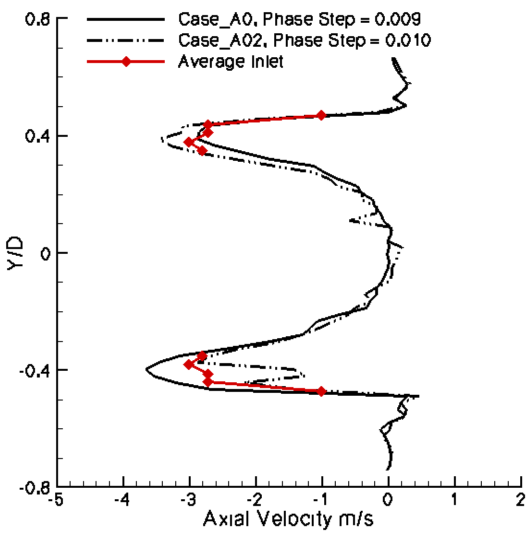

Figure 9: Axial velocities at fan inlet

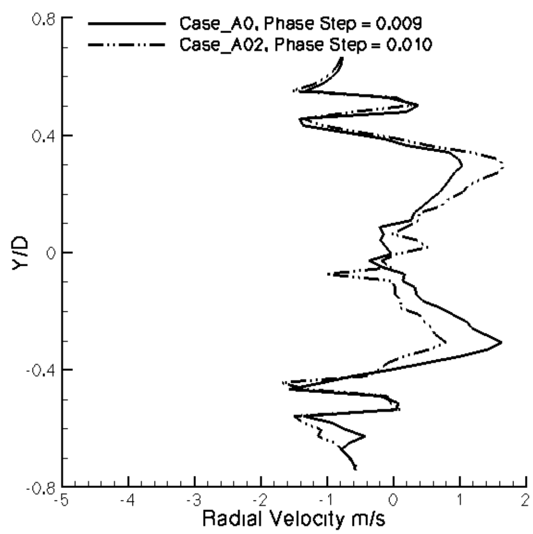

Figure 10: Radial velocities at fan inlet

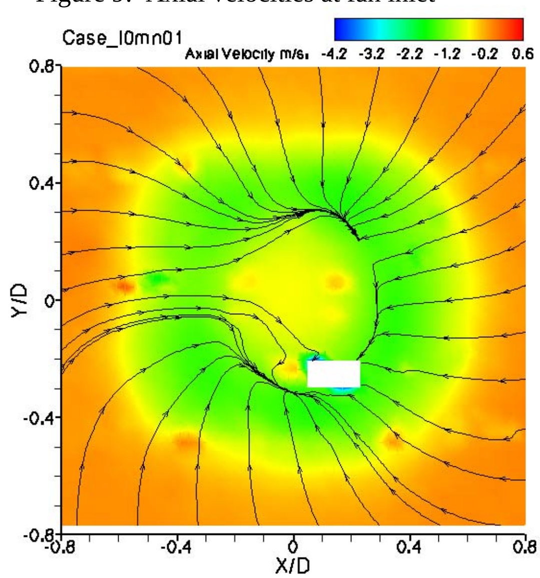

Figure 11: Axial velocity distribution 12.7 mm upstream of fan inlet

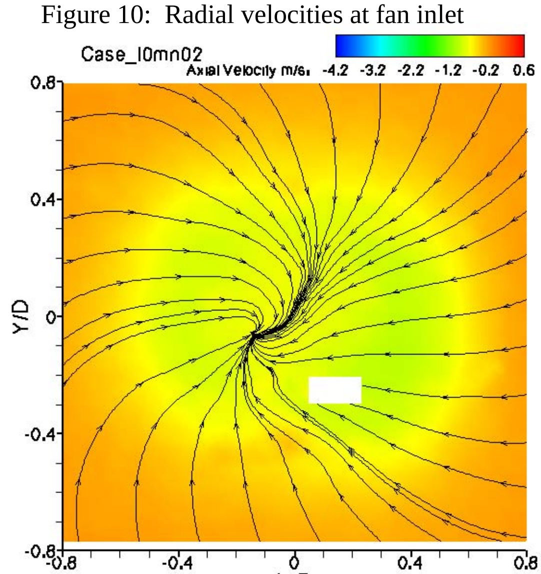

Figure 12: Axial velocity distribution 25.4 mm upstream of fan inlet

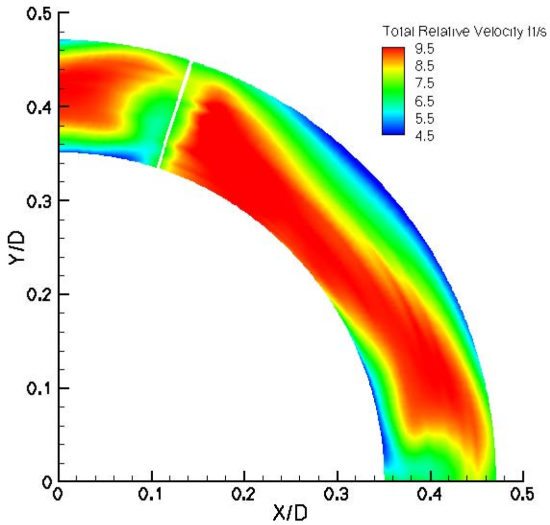

Figure 13: Total relative velocity distribution downstream of rotor blades and upstream of motor struts

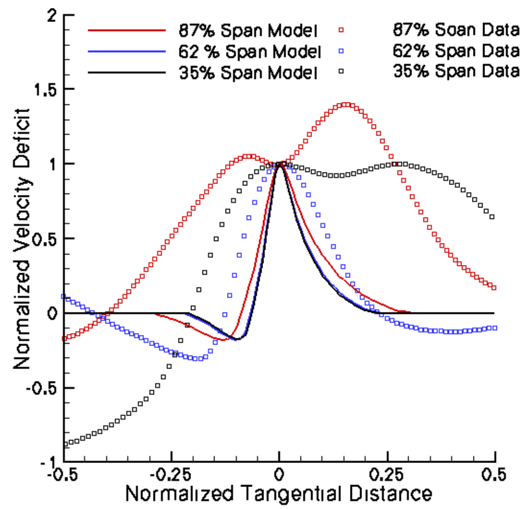

Figure 14: Comparison of modeled and measured normalized velocity deficits